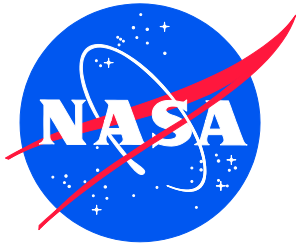


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Historical Perspective on Fast Coupled Loads Analysis Methods

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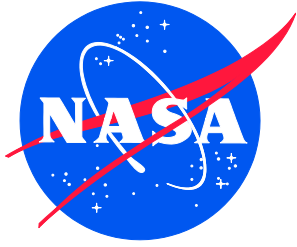
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Abstract

Spacecraft structural designs are typically verified through a coupled loads analysis (CLA) process, which couples the spacecraft model with the launch vehicle (LV) model to predict low-frequency quasi-static and dynamic responses. The CLA calculations are typically the responsibility of the LV organization, but the spacecraft organization has a vested interest in being able to calculate approximate CLA results during the design of the spacecraft. Because of this, there has long been interest in a method that would allow a spacecraft organization to perform a CLA without access to the full set of LV models and forcing functions. One such method is the Norton-Thevenin Receptance Coupling (NTRC) approach, which is specifically designed to accurately transform LV free accelerations (no payload) into coupled system accelerations (LV plus payload). The purpose of this report is to provide historical context for the NTRC method and compare it with methods that have been used in the past. In particular, it is compared to a frequency-domain substitution method that had been used for a long period of time at the Jet Propulsion Laboratory, and a component-mode-based equivalent to that method.

1.0 Introduction and Background

Spacecraft design organizations, including those within NASA, have long had an interest in being able to approximate the results of a coupled loads analysis (CLA) without access to all the models and forcing functions required to implement the approach taken by the launch vehicle (LV) contractor. This is often referred to as a “fast” CLA capability because the analysis can be run by the payload developer with shorter turnaround times than a standard CLA. A number of methods have been used for this purpose over the years. In particular, the Jet Propulsion Laboratory (JPL) has used a method often referred to as reanalysis, which combined results from a previous CLA with Hurty/Craig-Bampton (HCB) models of both the original and updated spacecraft to approximate the updated response [1][2]. This method was used for many years, although it was eventually replaced at JPL by the modal mass acceleration curve (MMAC) process. MMAC is designed to envelope rather than approximate a CLA, and JPL has come to the conclusion that it can result in more robust spacecraft designs. A method similar to the JPL reanalysis method was also developed that uses a component mode synthesis (CMS) approach, and that method has been successfully applied in a number of cases [3]. A report comparing these methods was written for NASA Engineering and Safety Center (NESC) in May of 2016 [4]. More recently, a Norton-Thevenin Receptance Coupling (NTRC) approach has been proposed and demonstrated to work very well for the cases studied. The purpose of this report is to provide a historical perspective on the NTRC approach and to enable a better understanding of how it compares with approaches used in the past.

The NTRC method for fast CLA is a substructure coupling approach that falls within a rich body of literature extending back for many years. Since the coupling is done in the frequency domain, NTRC is a frequency-response-based substructuring (FBS) method, as opposed to a CMS method. An excellent review of various approaches to substructure coupling is provided by de Klerk, Rixen, and Voormeeren [5]. Other references that are more specific to FBS methods include references [6]–[8]. A few works, such as reference [9], compare FBS and CMS methods and show that they are equivalent when the same input data is used (i.e., when frequency response functions (FRFs) are reconstructed from the same modes and residual terms). While the various methods for substructure coupling have different advantages and disadvantages, one focus in the literature has

been on the sensitivity of these methods to either errors in the coupled models or modal completeness, particularly in the context of experimental data where there is always noise in the measurements. References [10] and [11] address the particular question of robustness and sensitivity to uncertainty, pointing out cases where substructuring can be extremely sensitive to small errors in the measurements. For example, Ind [12] showed a case where adding just 1% noise to an FBS coupling problem resulted in completely erroneous results. Taking a modal view of the substructuring problem revealed that the modes needed to describe the motion of interest were very weakly represented in the measurements, so even though FBS was theoretically possible, it was extremely sensitive to noise. In general, works such as these tend to show that removing a substructure is typically a more numerically sensitive procedure than adding a substructure. The methods have also been extended to experimental data [13][14]. In these cases, CMS methods have typically been found to be more robust than FBS methods. This does not mean that FBS approaches do not work, but they must be applied carefully to achieve good results, particularly if test data is used as part of the process. However, in some applications, CMS methods are not practical—for example, when the system of interest contains high modal density such that it is not feasible to extract a modal model; in cases such as these, FBS has been successfully applied [15].

One important consideration in experimental substructuring, particularly when one subcomponent is being removed from another, is which degrees of freedom (DOFs) to use as the interface. Early works took the straightforward approach, removing one subcomponent from another using only the DOFs at the physical interface between the two substructures. However, Sjoval and Abrahamsson [14] later showed that using only the interface DOFs can lead to ill conditioning, essentially because the subcomponent that is being removed can have antiresonances in which all of the interface DOFs are fixed. They called these “generalized antiresonances” (GARs) and used them to explain why substructure uncoupling can result in large errors at some frequencies. This also explains why substructure uncoupling or decoupling becomes much more challenging if the component to be removed is flexible. Allen, Mayes, and Bergman addressed this issue using the transmission simulator method [13], and this idea was further elaborated on by D’Ambrogio and Fregolent [16], who termed it the extended interface method. This type of approach has now gained considerable traction in the international community.

Much of this work has focused on experimental rather than analytical substructuring, where the sensitivity to error is especially relevant. However, it has been the authors’ experience that FBS methods are sensitive to numerical truncation and need to be applied carefully. The NTRC authors have carefully addressed these issues and demonstrated excellent accuracy when the acceleration is correctly calculated.

There are multiple slightly different formulations of the FBS coupling equations in the literature. With some manipulation, most of them can be shown to be equivalent, but the most readily available reference for substructure coupling and FBS methods is probably Ewins [17], in which the FBS method is developed in section 6.4. Notably, multiple forms of the receptance coupling equation are shown, starting with

$$([H_a(\omega)]^{-1} + [H_b(\omega)]^{-1})^{-1}[H_a(\omega)]^{-1}$$

With a small amount of manipulation, and assuming that all matrices are full rank, this equation can be rewritten in either of the following two forms:

$$(I + [H_a(\omega)][H_b(\omega)]^{-1})^{-1}$$

or

$$[H_b(\omega)]([H_a(\omega)] + [H_b(\omega)])^{-1}$$

The first simplification replaces four inverses with two,¹ and the second reduces it to one, potentially improving numerical efficiency and robustness.² All three of these forms were utilized by the NTRC team in the early stages of numerical verification, after which they moved to a production version (n-body form) that was demonstrated in a problem that handled two payloads with different boundary conditions and damping regimes.

The primary purpose of this section, however, is to compare the NTRC method to two previously published methods specifically developed to perform a fast CLA based on previous CLA results. The first of these methods is the substitution analysis method used by JPL from the 1960s until approximately 2000 [1][2].³ This is an FBS method like NTRC and uses fast Fourier transforms (FFTs) to transform between the time and frequency domains. The second method is called time-domain reanalysis, which reformulates the JPL substitution analysis method in modal coordinates, avoiding the necessity of performing FFTs to transform between the time and frequency domains, and it is therefore more analogous to CMS methods [3]. We refer to these two approaches as the JPL frequency-domain substitution method and the time-domain substitution method, though it should be recognized that these are effectively just FBS-based and CMS-based approaches to solving the same problem. The methods are also described and applied to an example problem in a report to NESC [4].

While both methods have a goal very similar to that of NTRC, they are different in the sense that they assume the starting point to be a set of truncated system modes from a previous CLA that included a spacecraft (SC) model. This is predicated on the assumption that previous CLA results are more readily available than the free interface accelerance results required for NTRC. In this sense, NTRC is a special case of the substitution methods, where the previous SC had no mass or stiffness. On the other hand, the substitution methods are only modal approximations of NTRC in the sense that they assume that the interface accelerances are defined by the truncated CLA system modes. This is typically a poor assumption in the absence of a previous SC to mass load the interface, which is why the methods start from modes including an existing payload. NTRC addresses this by either using an HCB model for the LV or including free interface modes to a higher cutoff frequency than the CLA and adding residual vectors. The NTRC method is therefore less sensitive to changes in payload and more robust than either of the substitution methods.

In the following sections, we describe the two substitution methods and make some general observations as to how one might choose among these methods. Since it is impossible to treat substructuring without considering the very-well-developed CMS methods, some comments are also made on the direct application of CMS versus FBS to fast coupled loads.

¹ As we show later, this is effectively the form used in the JPL substitution method. In that case, $[H_b(\omega)]^{-1}$ is written directly in terms of the HCB equations for the spacecraft, so it only requires a single inverse.

² It is not always true that the formulation with the fewest inversions above is the best. For example, if an HCB model is used for one component or the other, the corresponding $[H(\omega)]^{-1}$ term can be calculated directly without inverting $[H(\omega)]$.

³ The alternative approach that has replaced substitution analysis at JPL is the modal mass acceleration curve (MMAC) method. This is a conservative bound on the CLA results and is therefore typically more robust than CLA.

1.1 JPL Frequency-Domain Substitution Method

The JPL frequency-domain method is the most analogous to NTRC in the sense that the coupling is performed in the frequency domain, with FFTs used to convert time-domain functions to the frequency domain and back. The method was used at JPL for many years (see, for example, reference [1]), but the most readily available reference is by Trubert and Peretti [2], in which the challenges of NTRC associated with transforming data from the time domain to the frequency domain and back again are discussed in some detail. Since this aspect is identical between the JPL substitution method and NTRC and is well developed in both cases, the focus here is on the frequency-domain part.

Reference [2] first derives a method to compute the interface accelerations of the coupled LV plus SC system from the accelerations of the LV with no SC (“free accelerations”), which is directly analogous to the NTRC method. It then generalizes this to the case where the payload is removed and substituted with another. The use of a set of truncated free-free modes in the JPL method, without any residual correction terms, would result in inaccurate system modes, but as far as the authors are aware, this method has always been used in the context of the substitution approach.

Besides the starting point, the primary difference between the JPL substitution method and NTRC is one of modal sufficiency. Since the JPL method is predicated on the assumption that the only available data are the truncated system modes from a previous coupled system, it depends on these being a sufficient basis to represent the modified coupled system. The JPL method would not be accurate for a free interface, since those modes would provide a very poor basis for the coupled system. However, although it is an approximation, it has proven to be fairly accurate for small to moderate changes in payloads. NTRC, on the other hand, utilizes a truncated set of LV free modes augmented with residual vectors to achieve an accurate solution. Because of this, NTRC does not depend on similarity of payloads for its accuracy and should be more accurate over a broad range of payloads.

To see the relationship between the two methods, start with the equation at the heart of the JPL method:

$$\ddot{U}_t(\omega) = \left[I - \left(\omega^2 \Phi_t (-\omega^2 + j\omega 2\zeta_q \omega_q + \omega_q^2)^{-1} \Phi_t^T \right) (M_{s2}(\omega) - M_{s1}(\omega)) \right]^{-1} \ddot{U}_{t0}(\omega)$$

where

Φ_t = Interface mode shape coefficients from the original CLA (LV coupled with original SC)

ω_q = Modal frequencies from the original CLA (LV coupled with original SC)

ζ_q = Modal damping ratios from the original CLA

$M_{s2}(\omega)$ = Interface apparent mass (F/A) for the new SC

$M_{s1}(\omega)$ = Interface apparent mass (F/A) for the original SC

$\ddot{U}_{t0}(\omega)$ = Interface acceleration from the original CLA (LV coupled with original SC)

If one starts with a free interface (no original SC), this reduces to

$$\ddot{U}_t(\omega) = \left[I - \left(\omega^2 \Phi_t (-\omega^2 + j\omega 2\zeta_q \omega_q + \omega_q^2)^{-1} \Phi_t^T \right) (M_{s2}(\omega)) \right]^{-1} \ddot{U}_{t0}(\omega)$$

At first glance, it is not obvious that this is equivalent to the NTRC equation, which is expressed as follows:

$$\ddot{U}_t(\omega) = [H_{ass}^{-1}(\omega) + H_{bss}^{-1}(\omega)]^{-1} H_{ass}^{-1}(\omega) \ddot{U}_{t0}(\omega)$$

where

$H_{ass}(\omega)$ = Interface accelerance (A/F) for the LV

$H_{bss}(\omega)$ = Interface accelerance (A/F) for the SC

To cast the NTRC equations into a form that is more consistent with the JPL free interface case, we utilize the following form from Ewins [17]:

$$\ddot{U}_t(\omega) = [I + H_{ass}(\omega)H_{bss}^{-1}(\omega)]^{-1} \ddot{U}_{t0}(\omega)$$

To see the similarities between the two methods, note that the JPL frequency-domain substitution equation $-\omega^2 \Phi_t (-\omega^2 + j\omega 2\omega_q + \omega_q^2)^{-1} \Phi_t^T$ is a modal approximation of NTRC's $H_{ass}(\omega)$. However, NTRC requires the LV in order to compute the interface accelerance utilizing the total flexibility at the interface via residual vectors, whereas the JPL method uses just a truncated set of free-free modes. Thus, the primary difference between the methods is shown to be the choice of modal basis, with the NTRC method using a modal basis that captures interface flexibility, whereas the JPL method is limited to the truncated modes available from the previous CLA.

1.2 Time-Domain Substitution

The time-domain substitution method [3] is not strictly a time-domain method but rather a CMS method that can be used in the frequency or time domain. However, it was developed specifically to avoid performing the solution in the frequency domain, with the corresponding requirements and difficulties of using an FFT, and it is therefore referred to as a time-domain method. The derivation of equations follows reference [2] fairly closely but retains modal coordinates. There are two submethods for time-domain substitution. The first derives the modified equations of motion in terms of the original modal generalized forces; this reduces to traditional CMS in the special case where the original system modes are replaced with a free interface CMS representation of the LV. The second method replaces the original modal generalized forces with the original motion of the interface; this is more closely aligned with the JPL method and follows the equations of reference [2] with exception of the transformation to the frequency domain. The final coupled equations for the second method are as follows:⁴

$$\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{Bmatrix} \ddot{\Delta}(t) \\ \ddot{u}_{q2}(t) \end{Bmatrix} + \begin{bmatrix} C_{11} & 0 \\ 0 & C_{22} \end{bmatrix} \begin{Bmatrix} \dot{\Delta}(t) \\ \dot{u}_{q2}(t) \end{Bmatrix} + \begin{bmatrix} K_{11} & 0 \\ 0 & K_{22} \end{bmatrix} \begin{Bmatrix} \Delta(t) \\ u_{q2}(t) \end{Bmatrix} = \begin{Bmatrix} F_1(t) \\ F_2(t) \end{Bmatrix}$$

$$u_t(t) = u_{t0}(t) + \Phi_t \Delta(t), \dot{u}_t(t) = \dot{u}_{t0}(t) + \Phi_t \dot{\Delta}(t), \ddot{u}_t(t) = \ddot{u}_{t0}(t) + \Phi_t \ddot{\Delta}(t)$$

Where:

$$M_{11} = \hat{M} - \Phi_a^T M_{aa1} \Phi_a + \Phi_t^T M_{tt2} \Phi_t$$

$$M_{12} = \Phi_t^T M_{tq2} = M_{21}^T$$

$$M_{22} = M_{qq2}$$

⁴ In these equations, the t subscript indicates the interface DOFs (common to all components), the $a1$ subscript indicates all DOFs of the original SC (interface plus modal), and $q2$ indicates the modal DOFs of the new SC.

$$\begin{aligned}
C_{11} &= \hat{C} - \Phi_a^T C_{aa1} \Phi_a \\
C_{22} &= C_{qq2} \\
K_{11} &= \hat{K} - \Phi_a^T k_{aa1} \Phi_a + \Phi_t^T K_{tt2} \Phi_t \\
k_{22} &= K_{qq2} \\
F_1(t) &= \Phi_a^T (M_{aa1} \ddot{u}_{a10}(t) + C_{aa1} \dot{u}_{a10}(t) + K_{aa1} u_{a10}(t)) - \Phi_t^T (M_{tt2} \ddot{u}_{t0}(t) + K_{tt2} u_{t0}(t)) \\
F_2(t) &= -M_{tq2} \ddot{u}_{t0}(t)
\end{aligned}$$

All the terms in the above equations are functions of modal parameters of the previous and current SC as well as the modes of the previous coupled system. The terms on the right-hand side are functions of the original payload motion ($u_{a0}(t)$, $\dot{u}_{a0}(t)$, $\ddot{u}_{a0}(t)$). This method does require more data than the JPL substitution method since the mode shape coefficients and motion of the entire original SC, rather than just the interface, are used as input.

If the starting point does not include a payload, the equations simplify considerably and the method becomes a reformulation of standard CMS methods where the input is the interface motion rather than forces on the LV.⁵ The first contribution of reference [3], therefore, is reformulating the CMS equations of motion to use the interface motion rather than forces applied to the LV as the inputs.

The second contribution of reference [3] is the recognition that for the case where the original SC exists and has modes, the coupled equations have a nonpositive definite mass matrix. This was found to be because the M_{11} matrix, which represents the effect of removing the original SC, is typically not of full rank. A solution for this problem was developed by performing a singular value decomposition (SVD) on M_{11} and removing “massless” DOFs before coupling the equations. This was found to provide a solution that is typically more robust than the JPL method, although it does require more data and an additional eigensolution. Also, it can be sensitive to the threshold chosen to identify massless DOFs.

To emulate the CLA process as closely as possible, the final coupled equations are usually diagonalized using a second eigensolution, before a standard time- or frequency-domain solution is applied to calculate dynamic response. This method, therefore, requires two eigensolutions on the order of the number of system modes. While this is not usually onerous for a single updated CLA with a reasonable number of system modes,⁶ it can become onerous for something like a Monte Carlo analysis where many solutions are required or for models with a very large number of modes (thousands or tens of thousands of modes).

ATA Engineering’s experience with this method is that it is usually more accurate than the JPL frequency-domain substitution method for the same number of system modes, possibly because it includes a more complete representation of the coupling to the original SC. However, it still suffers from inherent issues associated with removing a component from a coupled system, and as a result it is not likely to be as robust or accurate as a more traditional CMS approach that starts with a

⁵ However, like the JPL method, this would suffer from the fact that the free-free modes of the LV without any residual correction are typically a very poor basis for the coupled system equations.

⁶ The number of system modes in a typical CLA model can vary from hundreds to thousands. For hundreds of modes, this method is relatively fast; however, for thousands of modes, the eigensolutions can make it significantly slower than FRF-based synthesis methods.

sufficiently accurate representation of the LV, or the NTRC method which does the same in the frequency domain.

1.3 Traditional Component Mode Synthesis

Any discussion of potential approaches for performing a fast CLA cannot ignore traditional CMS-based methods. These methods, traditionally used for CLA, have been very well developed and refined over the years. A traditional CMS approach requires a modal representation of the LV, which can be based on either fixed or free interface modes (with residual flexibility) and the LV input forces. It is important to note that traditionally, most LV organizations have been reluctant to provide payload developers with proprietary models and forcing function to allow them to run a CLA. This led to the alternative CLA methods such as the JPL frequency-domain method, time-domain substitution technique, and most recently NTRC. However, if these models and forcing functions are available, the CMS-based CLA can typically be automated to run very quickly, and which method is fastest becomes very problem dependent.

1.4 Damping in Fast Coupled Loads

The treatment of damping throws another wrench into all these fast CLA methods. This is because there is no single way to represent damping in a CLA, and different damping methods will often be used for the same LV based on the circumstances. These methods can be generally classified into those that apply damping at the component level and those that apply damping at the system level. However, there are numerous variations, including the very popular Benfield-Hruda method [18][19], which combines component damping for the SC with damping on a set of intermediate mass-loaded modes for the LV. In some cases, the coupled damping matrix on the final system modes is carried through the integration of the equations of motion, and in others only the diagonal terms are retained. In many cases, where the damping on all components is consistent and relatively light, the difference due to damping treatment is small, but in some cases it can be significant. It is important, therefore, to understand the implicit assumptions on damping associated with the various fast CLA methods.

The two FBS methods implicitly assume that the SC damping is defined at the component level. The JPL frequency-domain substitution method can use any damping on the original CLA, but in practice, the assumption is that both the original CLA and the SC use diagonal damping. This is inconsistent since diagonal damping at the component level cannot result in diagonal damping at the system level, but it is typically close enough when damping is light and the same value is used for both the SC and the system. The NTRC method also assumes that the SC damping is defined at the component level, but it additionally assumes that the LV damping is defined at the component level. This is a rational model of damping, but it is very rarely the method used in practice for CLA. As in the case of the JPL method, the errors introduced by the implicit assumption on damping are typically small if the damping is light and consistent throughout the structure. Some care may be required, however, if this is not the case.

The CMS methods more closely emulate a standard CLA process and therefore are more amenable to treating damping in a way that is consistent with the CLA process. In particular, damping can be applied at either the component level or the system level, or using intermediate methods such as Benfield-Hruda. In addition, the final equations of motion can be integrated using a fully populated coupled damping matrix or by retaining only the diagonal elements.

It should be emphasized that for many practical problems, the differences in implementation of damping are negligible. However, there is a significant class of problems where they are not negligible and some care is required to ensure that implicit assumptions in damping do not lead to errors in results.

1.5 Concluding Remarks

All of the fast CLA methods discussed in this report are very closely related, and they are all effectively modal synthesis methods. That is because even if the synthesis is done in the frequency domain, it uses some set of modes to come up with the required FRFs. All the methods, therefore, depend upon the adequacy of the modal basis. In general, the use of a truncated set of free normal modes without correction will be an insufficient basis for accurate modal synthesis.

Some characteristics of the methods discussed in this report are summarized in Table 1.

Table 1. Comparison of fast coupled loads methods.

Method	LV Basis	SC Basis	FFT Required
JPL Substitution	Previous CLA modes	CMS	Yes
Time-Domain Substitution	Previous CLA modes	CMS	No
NTRC	Free modes + residuals	CMS	Yes
Traditional CMS	CMS	CMS	No

Historically, the JPL frequency-domain substitution method and the time-domain substitution method have been used in cases where the only data available is from a previous CLA. Both of these methods use truncated free normal modes without residual vector correction and are limited by the adequacy of the modes from the previous CLA in representing the LV interface. Neither of these methods can be used to reliably predict SC response from the results of an unloaded vehicle configuration, and they can be inaccurate when transforming the responses from one spacecraft to another if the dynamic characteristics or masses of the spacecraft are very different. However, in practice, they have been found to be fairly accurate in most practical situations.

To avoid these issues, NTRC takes the additional step of utilizing residual vectors to add back the truncated flexibility to ensure accurate substructure coupling. This is very closely related to the Rubin-MacNeal CMS method [20]. The analogy to NTRC in modal coordinates is traditional CMS, which also provides another avenue for fast CLA. Because of the limited applicability of a truncated mode set, the NTRC method will typically be more accurate than the substitution methods.

In summary, all of these fast CLA methods fall in the field of structural dynamic modification or substructure coupling. The JPL frequency-domain substitution method and NTRC are special cases of each other but have significant practical differences in implementation and accuracy due to the limitations of the modal basis used in the JPL method. The time-domain substitution method is a modal rather than an FRF synthesis method. It can be more robust than the JPL method but suffers from the same inherent limitation in the modal basis. However, it can also be computationally expensive for CLA models with thousands of modes. A fourth method is traditional CMS, which avoids the necessity of working in the frequency domain but requires potentially proprietary models and forcing functions.

A payload organization that wishes to perform a fast CLA can consider all four methods. If the LV CMS models and forcing functions are available, replicating the LV organization's CLA is likely to be the most accurate approach. In cases where the models and forcing functions are not available but the free interface accelerances can be obtained, the NTRC method is an excellent choice and will closely replicate the standard CLA results. The only approximations in this method are in its ability to exactly replicate the system-level damping often used for CLA and the need to transform back and forth between the time and frequency domains. In cases where neither the LV models nor accelerance data are available but the system modes from a previous CLA are known, either of the two substitution methods can often provide an acceptably accurate approximation. However, the user must be aware that the accuracy of these methods depends on the sufficiency of the original system modes, and that it can be difficult to ascertain exactly what level of accuracy will be obtained.

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14. ABSTRACT Spacecraft structural designs are typically verified through a coupled loads analysis (CLA) process, which couples the spacecraft model with the launch vehicle (LV) model to predict low-frequency quasi-static and dynamic responses. There has long been interest in a method that would allow a spacecraft organization to perform a CLA without access to the full set of LV models and forcing functions. One such method is the Norton-Thevenin Receptance Coupling (NTRC) approach. The purpose of this report is to provide historical context for the NTRC method and compare it with methods that have been used in the past.						
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